Autonomous Mission Operations Systems

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The Earth Observing One satellite is being used along with a variety of ground and flight software, other satellites, and ground sensors to prototype a sensor web.

Several ongoing related activities at the National Aeronautics and Space Administration (NASA)/Goddard Space Flight Center (GSFC) are acting together as pathfinders for future self-managing sensor constellations. Similar to commuters autonomously optimizing their route, future constellation components, whether they are orbital satellites, unmanned systems, or ground components, will autonomously optimize their operations activities. These systems will act independently while accomplishing coordinated observations that satisfy complex scientific objectives. Taken together, these smart components will enable more cost-effective management of future satellite constellations and other sensor platforms.

These pathfinder activities implement a operations approach integrating groups of autonomous sensor nodes to collaborate for observations. Autonomous event detections made by a source node are broadcast through the sensor web communications fabric in real time to trigger follow-up observation requests by other sensors and/or modeling elements. Middleware to enable interoperability between ground and space-based components provides a plug and play environment for new software and algorithms.

The sensor web technology activities use the Earth Observing 1 (EO-1) satellite[1] as an on-orbit testbed. EO-1 was launched November 21, 2000, as part of the New Millennium Program at NASA and was originally designed as a one-year mission to validate revolutionary space technologies. It hosts three land remote sensing instruments—the Advanced Land Imager, the Hyperion hyperspectral imager, and the Atmospheric Corrector—in addition to a dozen new, groundbreaking spacecraft

NASA's EO-1 satellite is used as an on-orbit testbed for exploring sensor web capabilities

Inside Track

- A series of ongoing experiments are being conducted at the NASA Goddard Space Flight Center to explore integrated ground and space-based software architectures that enable sensor webs.
- A sensor web is a coherent set of distributed nodes interconnected by a communications fabric that collectively behave as a single, dynamically adaptive, observing system.
- The nodes can be comprised of satellites, ground instruments, computing nodes, etc. Sensor web capability requires autonomous management of constellation resources.
- Autonomous management becomes progressively more important as more and more satellites share resources, such as communication channels and ground stations, while automatically coordinating their activities.

technologies. After its prime mission, it evolved into an orbital demonstration platform and, in particular, used to validate a number of sensor web concepts.

Figure 1 depicts a high level overview of key automation and autonomy capabilities integrated into the EO-1 mission. The highlights are as follows:

- Tasking of the EO-1 satellite with high level goals instead of specific commands.
- Onboard science processing, classification and autonomous decision-making.
- Autonomous triggers to task EO-1 from both the ground and other space-based assets.
- User interface to automatically sort and prioritize tasking requests. This includes building sensor web goal files and automatically uploading them to EO-1.

These capabilities continue to evolve and become more robust as the sensor web vision and architecture evolves.

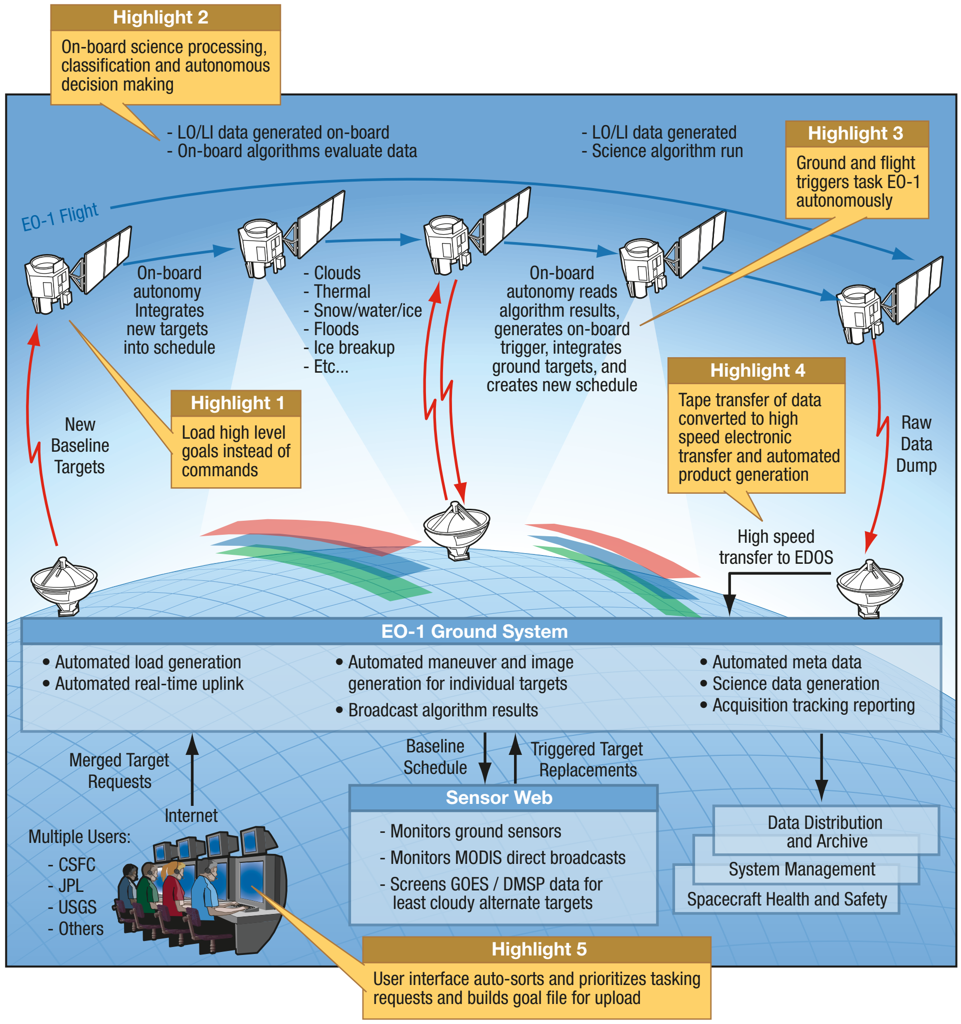

Figure 1. Overview of autonomy and automation software installed on the EO-1 mission.

Tasking EO-1 using high level goals

One of the key upgrades to the operations concept for EO-1 was to work with high-level goals instead of a series of individual low level commands and command loads.[2,3] A goal file consists of an objective statement with parameters that are uplinked to the spacecraft and expanded on-board into a prioritized sequence of individually commanded activities. This level of abstraction enables the user to be isolated from much of the underlying detail required to task the EO-1 satellite. When the original process of tasking EO-1 was defined, approximately 60 steps were required to task EO-1 for one image. When the autonomy and automation software was created, all of these steps were encapsulated in a few high-level goals by processing software that handles the underlying detail.

Ground system goal generation was done using both the Automated Scheduling and Planning Environment (ASPEN),[4] and a NASA Jet Propulsion Laboratory (JPL) application, and the Science Goal Monitor (SGM),[2] a GSFC application. The EO-1 spacecraft also creates high level goals on-board in addition to ingesting them from the ground via Continuous Activity Scheduling Planning Execution and Replanning (CASPER) software.[3] The CASPER software is an eight megabyte executable that is uploaded into memory on-board one of EO-1's flight processors and, once invoked, interprets the high-level goals on-board, manages the on-board details of acquiring an image and processing the data, and manages on-board replanning of the short-term integrated schedule of activities. Initially, the SGM was used as a pathfinder to encapsulate the high-level goals. Later, the ASPEN/CASPER combination was used.

Autonomous decision making

The Autonomous Sciencecraft Experiment (ASE), the centerpiece of the improved operations, provided the autonomy on-board EO-1.[4] ASE is comprised of CASPER and additional algorithms that can perform:

- Science data processing onboard.
- Classification of images to screen for clouds,[5] thermal anomalies, floods, change detection, generalized feature detection.[6]
- Selection of alternate targets without prior notice by replacing high-level goals in the on-board goal file. The replacements can either be triggered on-board by one of the classifiers or can be loaded from the ground as a result of an autonomous trigger from another node in the sensor web.

In the beginning of the mission, all tasking of EO-1 to perform imaging with its three instruments was meticulously planned by a team of scientists, engineers, and operations personnel on a daily basis. Over the last two years, the operations concept has evolved to the point that autonomous triggers can task EO-1 without continuous human intervention. In the sensor web experiments, transient events such as volcano eruptions trigger EO-1 images via ASPEN or SGM. These triggers are folded into the normal tasking plan via a priority scheme which enables higher priority tasking requests to automatically replace lower priority tasking requests in the onboard schedule. The planning process is now greatly simplified since we are dealing with a higher level of abstraction than in the beginning of the mission.

Figure 2 depicts various sensor web experiments that have been conducted. Note the variety of software tools used and the variety of applications. Autonomous triggers included other satellites, such as Terra, Aqua, and the Geostationary Operational Environmental Satellites (GOES), as well as ground instruments, such as the tilt meter installations to detect volcanic activity at Kilauea, Hawaii.

User interfaces and communications fabric

A Web interface has been prototyped that provides a mechanism to input tasking requests. Up to now, the customer interface for tasking requests originated at the US Geological Survey (USGS) Center for Earth Resource Observations and Science (EROS). This required weekly meetings with the EROS representatives, the GSFC flight operations team, EO-1 mission engineers, and the EO-1 project science team to integrate the various customer requests. However, on the new system, all of the priority schemes have been encoded in software, so the weekly meetings will become the exception. The translation of tasking requests to uplinkable goal files as well as the uplink and ingest on-board are all automated.

The key to making sensor webs work is the communications fabric that exists between the various software applications. Inter-process communications is readily available for ground-to-ground based software processes. However, sensor webs require communications between software applications that are resident onboard satellites and the ground. Therefore, for the experiments we devised a software bus onboard EO-1 in which any application can address any other application and easily send a message as a means to coordinate activities. This concept was extended by using Internet technology interfaces to create a virtual connection between satellites, such as using the Terra satellite as a triggering source for locating hot pixels from volcano eruptions and tasking the EO-1 satellite with follow-up observation requests. An Internet site was used to create a virtual connection between ground instruments, such as tilt meters installed on the Kilauea volcano, EO-1's planning software, and the EO-1 satellite. System responsiveness is improved by using Internet protocol.

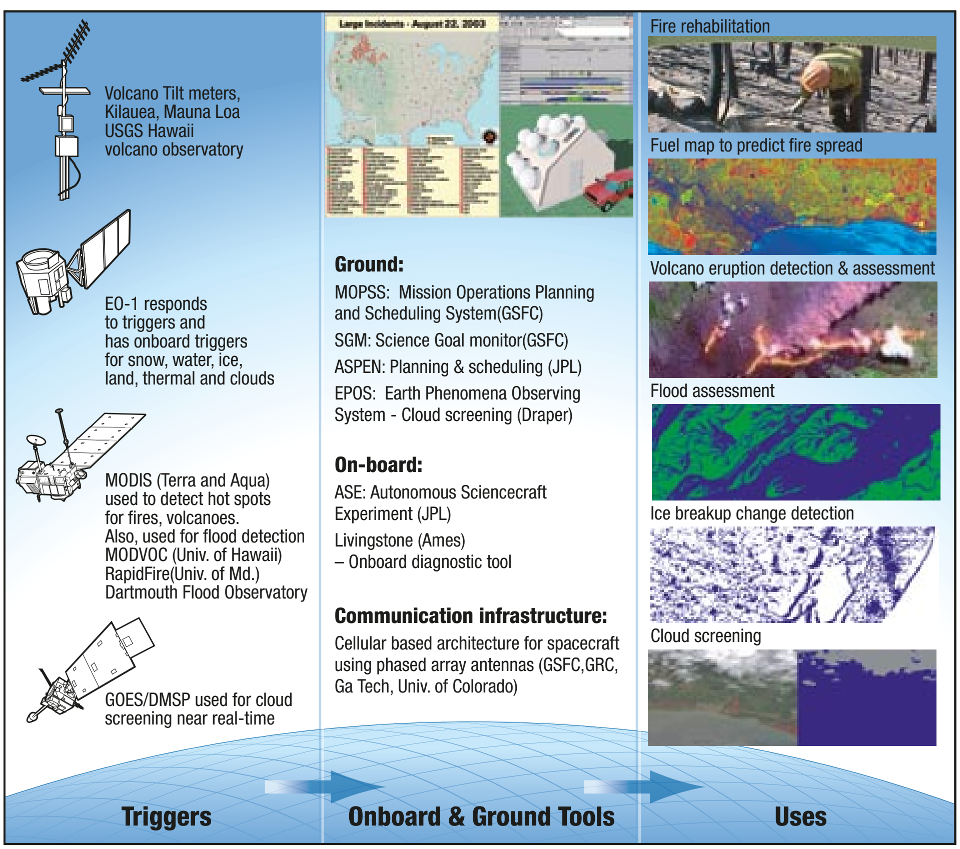

Figure 2. Overview of the various triggering combinations along with some of the applications that were used with EO-1.

Lessons learned and future implications

By treating every component in a constellation as a network-based software component, we can create a collaborative environment that enables sensor webs. The key to the successes on EO-1 resided in the fact that EO-1 was built with two on-board computer processors with additional memory which is modifiable on-orbit. Future missions should be built with additional computing resources to enable new software applications to be installed on-orbit as mission experience and innovative new thinking extends beyond initial mission plans.

Experimental results in mission autonomy allowed us to explore the constraints related to conflict resolution for competing triggering requests. In addition, the implementation of fully automated systems uncovered error conditions that were a result of interaction with pre-existing operations procedures. As these problems were identified, additional intelligence was added to queuing scripts and ingest routines to eliminate these glitches. Many of these lessons were learned during on-orbit debugging of new code installations, since many of the functions could not be fully checked on the ground due to limitations in flight software simulators.

Figure 3 represents a future vision in which software can be loaded onto satellites in a "plug and play" manner so as not to require extensive integration and testing. Efforts such as these and other related activities are going to enable increased flexibility and thus cost-effective sensor webs.

As an indirect result of the experiments conducted on EO-1, which added various autonomy and automation software components on both the ground and on-board the satellite, operations costs have dropped dramatically. It is expected that the actual cost of operations will drop further in the totally automated mode planned to begin fiscal year 2006. Figure 4 depicts the monthly cost of operating the EO-1 mission, where the solid line depicts the actual costs and the dashed line depicts the projected monthly cost as new software components are installed into operations.

Clearly, connecting software components to create sensor webs and increasing autonomy validated future operations concepts and created the immediate benefits of reducing cost and enabling additional science.❖

Figure 3. Sensor web vision with seamless communications between space and ground software elements.

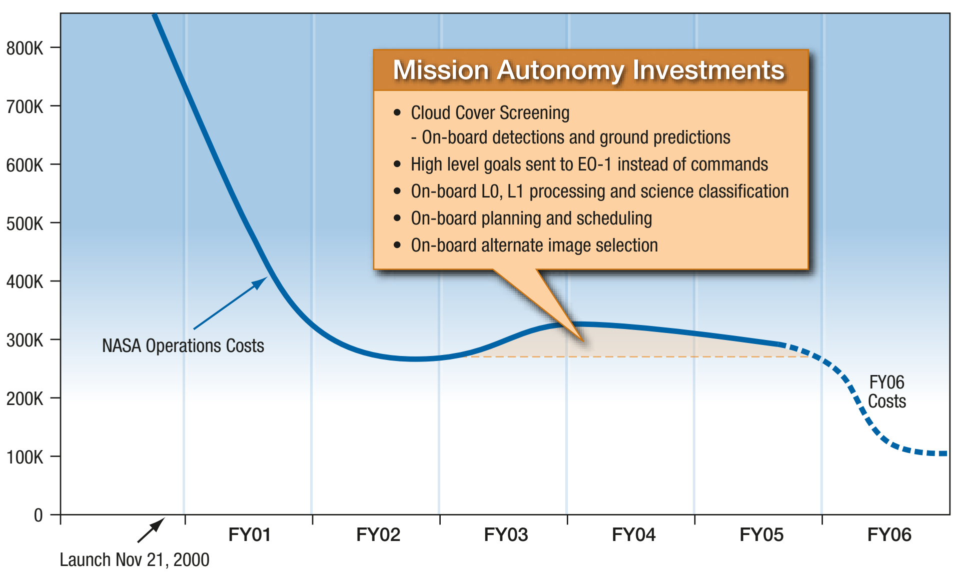

Figure 4. Cost profile of EO-1 with key software components identified on the inset box.

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